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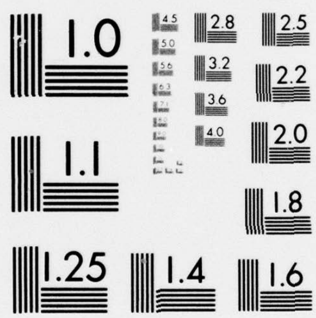

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RESERVOIRS AND INDUCED SEISMICITY AT CORPS OF ENGINEERS PROJECTS

by

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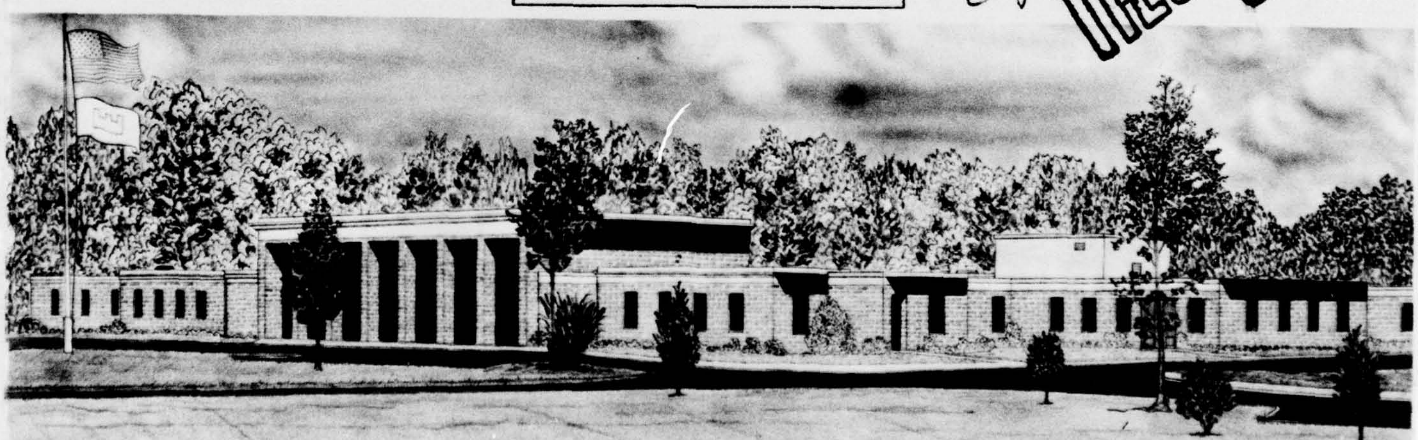

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A review was made of major reservoirs of the Corps of Engineers with regard to their experiences with induced seismicity. The Corps has 24 large reservoirs, i.e. those with dams 60.96 m (200 ft) in height or greater, and with volumes of 1233.5×10^6 m^3 (1,000,000 acre-ft) or greater. There also are 10 dams that are 91.44 m (300 ft) high, or higher, but with reservoirs of less than 1233.5×10^6 m^3. Thirteen reservoirs ~~have been~~ were instrumented for monitoring microearthquakes. They range from large to small and are located → next page
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cont. in aseismic to highly seismic areas. Only one Corps reservoir, Clark Hill in Georgia-South Carolina, has experienced a felt earthquake, but the 21-year interval between impoundment and the occurrence of the earthquake is not typical of reservoir-induced earthquakes and a direct relationship appears improbable.

PREFACE

This report is part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) in Civil Works Investigation Studies, "Seismic Effects of Reservoir Loading and Fluid Injection," sponsored by the Office, Chief of Engineers (OCE).

General direction was by Mr. James P. Sale, Chief, Soils and Pavements Laboratory. COL John L. Cannon, CE, and Mr. F. R. Brown were Director and Technical Director, respectively, of WES during the period of this study.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
acre-feet	1233.482	cubic metres
feet per day	0.3048	metres per day

RESERVOIRS AND INDUCED SEISMICITY AT CORPS OF ENGINEERS PROJECTS

PART I: INTRODUCTION

1. The U. S. Army Corps of Engineers (CE) has prime responsibility for flood control in the United States. Thus, they have constructed a large number of dams with small to very large reservoirs. The reservoirs store excess water, which is later released as necessary. Consequently, the levels of flood control reservoirs fluctuate greatly. Sometimes there are pools for power, irrigation and water supply, navigation, and recreation. Where power is generated, allowable fluctuations are restricted. The larger reservoirs of the Corps serve mostly a dual purpose, principally flood control and power.

2. A "large" reservoir is defined by the National Academy of Sciences[1] as a reservoir with 1,000,000 or more acre-ft* (1233.5×10^6 m^3) of water, usually impounded by a dam 300 ft (91.44 m) or greater in height. The Corps has four such dams: Abiquiu, Dworshak, Libby, and Pine Flat. A fifth, New Melones, is under construction. These dams are listed in Table 1, which includes all CE dams higher than 200 ft (60.96 m) and with reservoirs greater than 1,000,000 acre-ft (1233.5×10^6 m^3). Table 1 includes 19 dams that are between 200 ft (60.96 m) and 300 ft (91.44 m) in height and have reservoirs greater than 1,000,000 acre-ft (1233.5×10^6 m^3). Locations of the dams are shown in Figure 1.

3. Table 2 lists 10 additional CE dams that are greater than 91.44 m high but with reservoirs that are less than 1233.5×10^6 m^3.

4. Table 3 lists all CE reservoirs that have been instrumented to record microearthquakes that might be the result of induced seismicity from reservoir loading. There are 13 such reservoirs, counting

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

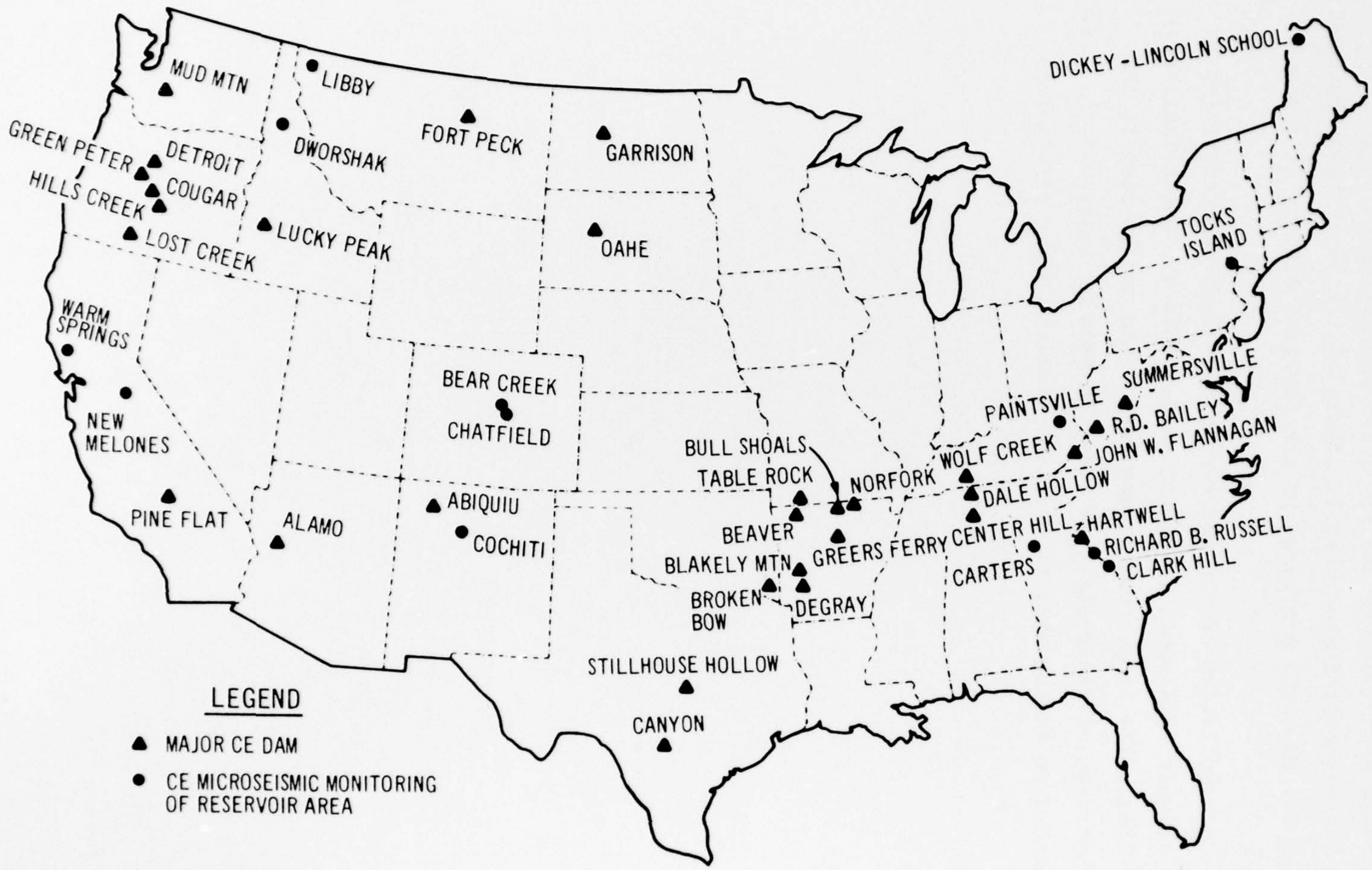

Figure 1. Location of major CE projects and of reservoirs instrumented for microearthquake monitoring

Dickey-Lincoln School as one reservoir for monitoring purposes. Locations of the reservoirs are shown in Figure 1. Three of them (Dworshak, Libby, and New Melones) are large by the National Academy of Sciences definition.

5. A compilation of the above-mentioned dams and reservoirs in terms of seismic risk zones is presented in Table 4. The seismic risk zones are basically those from Algermissen.[2] As can be seen in the table, instrumented reservoirs are found in each of zones 0 to 4, i.e. from areas of no earthquakes to areas of frequent major earthquakes.

PART II: PRELIMINARY APPRAISAL OF RESERVOIR EFFECTS

Survey of Felt Earthquakes

6. A preliminary assessment of the effects of reservoir filling was made by contacting Corps personnel responsible for the various reservoir and dam projects.

7. The survey of available information indicates that in only one instance (Clark Hill Dam, 1974) has a felt earthquake occurred at a CE reservoir. This applies to projects located in both seismic and nonseismic areas.

Reservoir Fluctuations

8. The survey included some cases where unusually heavy rainfall caused rapid filling of the reservoir. For example, a severe storm in March 1952 caused over 4,000,000 acre-ft of water to be stored in the reservoir at Wolf Creek Dam in a week or two. At the same time, over 2,000,000 acre-ft were added to the reservoir at Dale Hollow Dam, about 20 miles away. Another similar case of rapid reservoir filling occurred at Center Hill Dam in 1949 when about 1,330,000 acre-ft of water were suddenly added to the reservoir. In the spring of 1972 the reservoir at Libby Dam rose about 250 ft in 4 months (2.1 ft/day), and the reservoir at Cougar Dam rose about 290 ft in 7-1/2 months (1.3 ft/day). Similar rises have occurred at other reservoirs. Tables 1 to 3 show the contrasts that can exist between minimum and maximum reservoir volumes. Large reservoir fluctuations should be favorable for occurrence of reservoir-induced earthquakes, but at none of the projects with extreme reservoir changes did a perceptible earthquake occur.

Clark Hill Reservoir

9. The single felt earthquake located in close proximity to a CE reservoir was the 2 August 1974 South Carolina earthquake at the

Clark Hill Reservoir.[3] The local magnitude (M_L) was 4.3. The epicentral area (see Figure 2) was within a few kilometres of the northern part of the reservoir. The only other felt earthquake of record in this area had a Modified Mercalli (MM) intensity of VI and occurred near Lincolnton, Georgia, on 1 November 1875 (see Coffman and von Hake[4]).

10. Lincolnton is about 15 km from the epicentral area of the 1974 event (see Figure 2 for locations). The Clark Hill Reservoir had been impounded since 1953, or 21 years before the 1974 earthquake occurred. This long time interval between impoundment and the earthquake is not typical of reservoir-induced earthquakes. Thus, a relation between the reservoir and this earthquake is not evident and appears unlikely. The occurrence of the Lincolnton earthquake suggests that the 1974 earthquake might have happened were the reservoir not there.

Microearthquake Monitoring at CE Projects

11. Reservoirs of the Corps with programs for microearthquake monitoring are listed in Table 3. Microearthquakes are events with magnitudes less than 3.5 and are detected only by instruments.

12. Data from instrumented sites can be studied for a variety of purposes in addition to determining reservoir effects. They can be processed to delineate fault planes, to identify centers of activity and subsequent movements of activity along fault planes, and to determine focal mechanisms. The installation at Bear Creek, Colorado, may be of special interest, since the reservoir will inundate a known active fault, as evidenced from epicenter locations determined from small earthquakes. It is expected that monitoring during filling of reservoirs will enable the Corps to respond effectively should evidence point to a marked increase in seismicity. Also, such data may be useful for developing remedial measures that are speculative at present.

13. Patrick[5] made a detailed review of microearthquake monitoring at CE reservoirs. The CE experience can be summarized as follows:

a. Reservoirs without observed microearthquakes.

(1) Carters. No local seismicity.

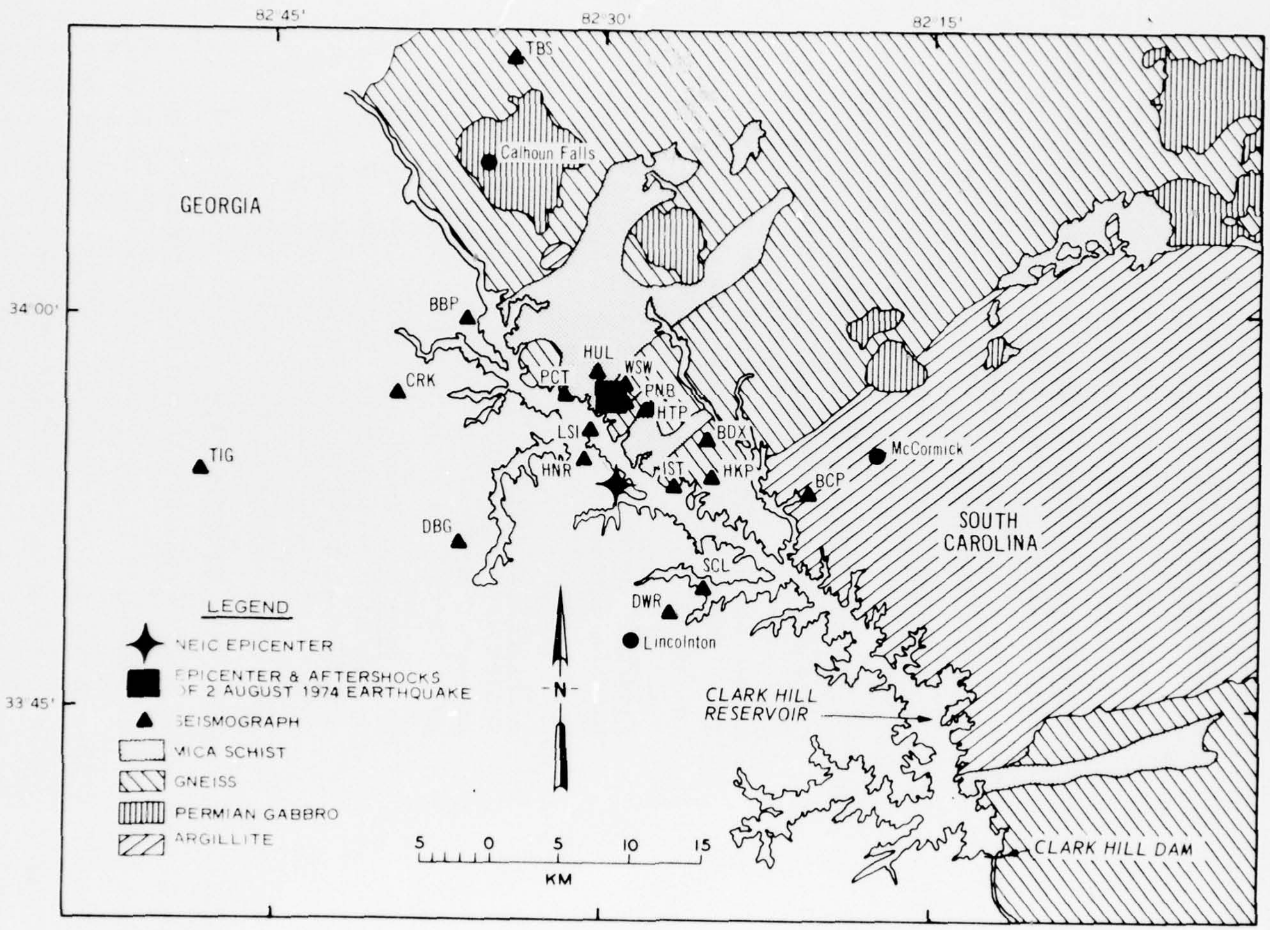

Figure 2. General geology and location of 2 August 1974 earthquake and aftershocks near Clark Hill Reservoir (after Talwani[3])

(2) <u>Chatfield and Bear Creek.</u> Chatfield: pool not yet established. Bear Creek: under construction, no positive microearthquakes; some possible.

(3) <u>Cochiti.</u> No local seismicity.

(4) <u>Dickey-Lincoln School.</u> Proposed project. Not yet under construction. Stations beginning to operate.

(5) <u>New Melones.</u> Under construction. Three years of monitoring show no local events.

(6) <u>Paintsville.</u> Preconstruction observations. Results indeterminate.

(7) <u>Richard B. Russell.</u> Under construction. Station not yet operating.

(8) <u>Tocks Island.</u> Abandoned project. Preliminary observations. Few questionable events.

b. <u>Reservoirs with local microearthquakes:</u>

(1) <u>Clark Hill.</u> Short intervals of observations by Professors L. T. Long of Georgia Institute of Technology and Pradeep Talwani of the University of South Carolina have revealed local microearthquakes. The seismicity may or may not be relatable to local fault trends. A relation between seismicity and reservoir levels has been postulated (see Talwani[3]) but the period of observation is insufficient to permit specific conclusions.

(2) <u>Libby and Dworshak.</u> Monitored before filling of reservoirs and after filling in 1971-72 until the present. Numerous microearthquakes. No relation of seismicity to reservoir conditions.

(3) <u>Warm Springs.</u> Under construction. No pool. Numerous microearthquakes: 293 between 1 January 1974 and 17 August 1975. Highly seismic area.

14. Fort Peck Reservoir was never instrumented for microearthquake activity; however, data accumulated in 1966 to 1968 by the Large Aperture Seismic Array (LASA), installed to monitor nuclear blasts in the Soviet Union, were restudied to see if there were microearthquakes at the reservoir (see Marcuson and Krinitzsky[6]). Three events were found at distances of 30 to 50 miles from the main reservoir. Thus, the Fort Peck Reservoir either is the scene of very low seismic activity or none at all.

15. Clark Hill is the only CE reservoir with a felt earthquake

in close proximity. Also, it is the only CE reservoir in which microseismicity has been inferred to be related to reservoir levels. The relation between seismicity and reservoir level is based on measurements taken during a 3-month period about 7-1/2 months after the 2 August 1974 earthquake. The reservoir level had a rise of 5 ft in 3 days during the time of these observations. Talwani noticed a corresponding increase in seismic activity with a 2-day lag. The relation is shown in Figure 3, taken from Talwani.[3] The short period of observation is insufficient to demonstrate a conclusive relationship between the small reservoir rise of 5 ft in 3 days and the increase in microearthquake activity. The record of microearthquake activity at Libby Dam shows that an observational period of 2 years before reservoir filling may be necessary to avoid incorrect inferences between reservoir stage and microearthquake activity.

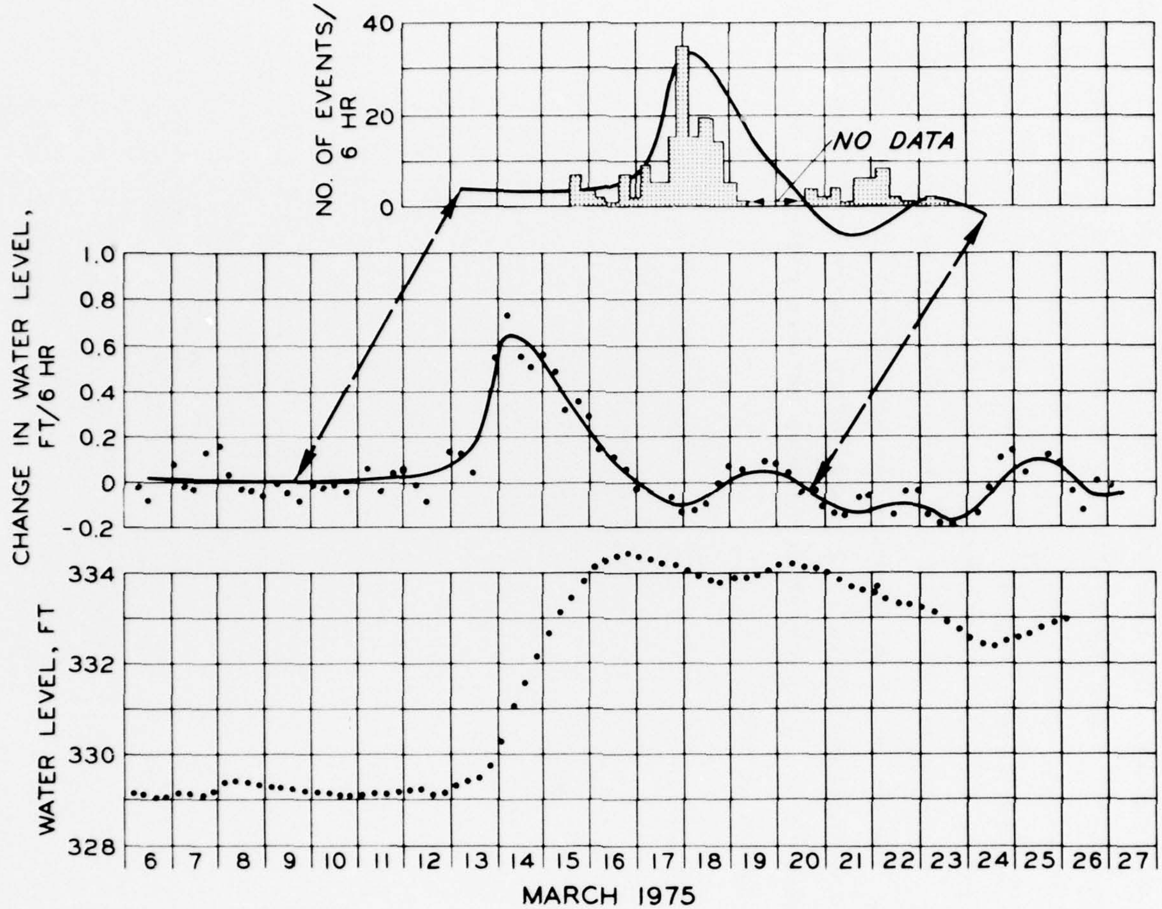

Figure 3. Relation of water level in Clark Hill Reservoir to local seismicity (from Talwani[3])

PART III: CONCLUSIONS

16. With the exception of Clark Hill, no reservoir of the Corps of Engineers has experienced a felt earthquake. Included are all of the major reservoirs, several with large fluctuations in pool size, and locations in aseismic to very seismic regions.

17. The felt earthquake at Clark Hill that occurred in 1974 probably is not related to the reservoir since the earthquake occurred 21 years after the reservoir was filled. Reservoir-induced earthquakes appear to occur upon reservoir filling and for 5 or 10 years afterwards, but are not known to have occurred 21 years after impoundment. Microearthquakes at Clark Hill have been interpreted by Talwani[3] to be influenced by fluctuations in reservoir level. Further observations will be made and are desirable, since observations at Libby Dam have shown that an observational period of 2 years before reservoir filling is necessary to avoid incorrect inferences between reservoir stage and microearthquake activity.

18. A program of microearthquake observations has been undertaken at thirteen CE reservoirs ranging from small to very large and located in areas of low seismicity to major seismicity.

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Table 1

CE Dams >60.96 m (200 ft) High and with Reservoirs >1233.5 × 10^6 m^3 (1,000,000 acre-ft)

Dam	Use*	State	River	Dam Height m	Reservoir Capacity, $m^3 \times 10^6$ Max	Normal	Min	Reservoir Filling Date Started	Date Completed
Abiquiu	FC	New Mexico	Rio Chama	97.54	1,702.17	--	54.27	1963	1963
Alamo	FC	Arizona	Bill Williams	83.82	1,288.94	11.96	?	1969	1970
Beaver	FC, P	Arkansas	White	69.45	2,691.41	2,037.68	896.73	1963	1965
Blakely Mountain	FC, P	Arkansas	Ouachita	70.10	3,414.22	2,653.17	1065.71	1952	1955
Broken Bow	FC, P	Oklahoma	Mountain Fork	68.58	1,976.00	1,133.55	553.82	1968	1969
Bull Shoals	FC, P	Arkansas	White	78.03	7,416.79	3,759.59	2522.43	1951	1952
Canyon	FC	Texas	Guadalupe	68.28	1,392.58	476.12	426.78	1964	1968
Center Hill	FC, P	Tennessee	Caney Fork	68.88	2,580.40	1,640.50	1031.17	1950	1950
Dale Hollow	FC, P	Tennessee	Obey	60.96	2,104.28	1,668.87	1057.08	1943	1944
DeGray	FC, P	Arkansas	Caddo	74.07	1,087.91	806.68	321.93	1969	1971
Dworshak	FC, P	Idaho	Clearwater	218.54	4,393.58	4,277.64	1790.98	1971	1973
Fort Peck	FC, P	Montana	Missouri	76.20	23,559.09	22,325.63	5303.88	1937	1942
Garrison	FC, P	North Dakota	Missouri	61.57	30,096.42	28,246.23	6167.30	1953	1955
Greers Ferry	FC, P	Arkansas	Little Red	74.07	4,086.45	2,355.91	?	1962	1964
Hartwell	FC, P	Georgia-South Carolina	Savannah	62.18	3,505.49	3,144.09	2515.02	1961	1962
John W. Flannagan	FC	Virginia	Pound	79.25	1,797.15	82.64	61.67	1965	1967
Libby	FC, P	Montana	Kootenai	112.78	7,165.17	2,260.93	1079.28	1972	1972
New Melones**	FC, P	California	Stanislaus	190.50	3,453.69	382.37	?	--	--
Norfork	FC, P	Arkansas	White	67.67	2,600.13	1,543.06	990.47	1943	1944
Oahe	FC, P	South Dakota	Missouri	74.66	29,109.66	27,752.85	6784.03	1958	1962
Pine Flat	FC	California	Kings	131.06	1,233.46	647.57	246.69	1958	1958
Stillhouse Hollow	FC	Texas	Lampasas	60.96	1,249.49	777.08	289.86	1968	1969
Table Rock	FC, P	Missouri	White	76.81	5,026.35	3,332.81	1874.86	1958	1959
Wolf Creek	FC, P	Kentucky	Cumberland	71.02	7,510.72	4,927.67	2285.60	1951	1951

* FC = flood control; P = power.
** Under construction.

Table 2

CE Dams >91.44 m (300 ft) High and with Reservoirs <1233.5 × 10^6 m^3 (1,000,000 acre-ft)

				Dam	Reservoir Capacity $m^3 \times 10^6$			Reservoir Filling	
Dam	Use*	State	River	Height m	Max	Normal	Min	Date Started	Date Completed
Carters	FC, P	Georgia	Coosawatee	136.25	583.45	465.03	226.96	1974	1975
Cougar	FC, P	Oregon	South Fork	135.64	270.14	78.94	66.61	1963	1964
Detroit	FC, P	Oregon	North Santian	138.38	583.45	561.24	141.85	1952	1953
Green Peter	FC, P	Oregon	Middle Santian	106.68	527.98	197.36	119.65	1966	1968
Hills Creek	FC, P	Oregon	Willamette	103.02	439.11	191.19	131.98	1961	1962
Lost Creek**	FC, P	Oregon	Rogue	99.67	532.85	351.54	207.22	1976	--
Lucky Peak	FC	Idaho	Boise	103.63	421.84	361.40	35.77	1954	1955
Mud Mountain	FC	Washington	White	129.54	130.75	--	0	1948	?
R. D. Bailey**	FC	West Virginia	Guyandot	94.49	250.39	41.94	33.30	--	--
Summersville	FC	West Virginia	Gauley	111.25	509.42	235.59	33.30	1965	1966

* FC = flood control; P = power.

** Under construction.

Table 3

CE Reservoirs with Microearthquake Monitoring for Induced Seismicity

Dam	Use*	State	River	Dam Height m	Reservoir Capacity $m^3 \times 10^6$ Max	Normal	Min	Reservoir Filling Date Started	Date Completed
Bear Creek**	FC	Colorado	Bear Creek	54.71	67.84	34.54	2.47	--	--
Carters	FC, P	Georgia	Coosawatee	136.25	583.43	465.01	226.96	1974	1975
Chatfield	FC	Colorado	South Platte	44.81	437.88	289.86	29.60	1973	--
Clark Hill	FC, P	Georgia-South Carolina	Savannah	60.96	3577.03	3095.98	1807.02	1951	1953
Cochiti	FC	New Mexico	Rio Grande	76.50	893.05	59.21	59.21	1975	1976
Dickey†	FC, P	Maine	St. John	102.11	9497.64	8017.49	5920.61	--	--
Lincoln School†	FC, P	Maine	St. John	25.91	107.31	--	34.54	--	--
Dworshak	FC, P	Idaho	Clearwater	218.54	4393.58	4277.64	1790.98	1971	1973
Libby	FC, P	Montana	Kootenai	112.78	7165.17	2260.93	1079.28	1972	1972
New Melones**	FC, P	California	Stanislaus	190.50	2960.30	382.37	382.37	--	--
Paintsville**	FC	Kentucky	Paint Creek	48.77	90.04	50.57	4.93	--	--
Richard B. Russell**	FC, P	Georgia-South Carolina	Savannah	55.44	1265.53	1201.39	1108.88	--	--
Tocks Island††	FC, P	Pennsylvania-New Jersey	Delaware	48.77	1042.27	642.63	118.41	--	--
Warm Springs**	FC	California	Dry Creek	97.23	469.95	302.20	24.67	--	--

* FC = flood control; P = power.
** Under construction.
† Proposed.
†† Discontinued project.

Table 4

Seismic Risk Zones for Major CE Dams and for CE Reservoirs Instrumented for Microearthquakes

Seismic Zone 0: No Earthquakes

Canyon, Texas
Stillhouse Hollow, Texas

Seismic Zone 1: Minor Earthquakes

Bear Creek, Colorado*
Beaver, Arkansas
Blakely Mountain, Arkansas
Broken Bow, Oklahoma
Bull Shoals, Arkansas
Center Hill, Tennessee
Chatfield, Colorado*
Dale Hollow, Tennessee
DeGray, Arkansas
Fort Peck, Montana
Garrison, North Dakota
Greers Ferry, Arkansas
Oahe, South Dakota
Paintsville, Kentucky*
Summersville, West Virginia
Table Rock, Missouri
Tocks Island, Pennsylvania-New Jersey*,**

Seismic Zone 2: Moderate Earthquakes

Abiquiu, New Mexico
Alamo, Arizona
Carters, Georgia*

Seismic Zone 2 (Continued)

Clark Hill, Georgia-South Carolina*
Cochiti, New Mexico
Cougar, Oregon
Detroit, Oregon
Dworshak, Idaho*
Green Peter, Oregon
Hartwell, Georgia-South Carolina
Hills Creek, Oregon
John W. Flannagan, Virginia
Libby, Montana*
Lost Creek, Oregon
Lucky Peak, Idaho
Mud Mountain, Washington
Norfork, Arkansas
R. D. Bailey, West Virginia
Richard B. Russell, Georgia-South Carolina*
Wolf Creek, Kentucky

Seismic Zone 3: Major Earthquakes

Dickey-Lincoln School, Maine†
New Melones, California*

Seismic Zone 4: Frequent Major Earthquakes

Pine Flat, California
Warm Springs, California*

* Instrumented for microearthquakes.
** Discontinued project.
† Proposed project.

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